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**FENSAP-ICE :
Applications to
Complete Rotorcraft Configurations**

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Outline

- Introduction
- Computational Approach
- Numerical Results
- Conclusions
- Future Work



Introduction (1)

- Traditionally, rotorcraft have limitations on operations in icing conditions
- Objective to produce affordable all-weather rotorcraft
- Means selected is to improve numerical simulation methods to reduce and focus development testing



Introduction (2)

- Develop a full 3-D rotorcraft icing simulation system
- Run development test cases with increasing geometrical complexity from 2-D airfoil to full rotorcraft including rotors
- Use existing CFD 3-D technology and apply to icing field
- Benefit from cross-pollination from fields such as blood flow simulation or combustion



Introduction (3)

- It is believed that SLD requirements such as coalescence, breakup and splashing can be modeled using mature technology from other fields
- Method must not discriminate according to geometry analyzed (nacelle vs. wing) but must be generic enough to handle all bodies in similar fashion
- Resulting tool must be upgradeable, synchronous with tools used in Aero, traceable



Introduction (4)

- 3-D CFD may be thought to be expensive but the *incremental* cost of icing analysis is small compared to generating meshes and solving viscous flows
- Such meshes and viscous flow solutions have in general already been carried out by Aero or CFD groups. Ignoring them for icing analysis is a waste of valuable information
- 3-D CFD cost is small compared to experimental testing
- 3-D CFD cost pales when compared to flight testing
- 3-D CFD is used to complement or focus development or certification testing



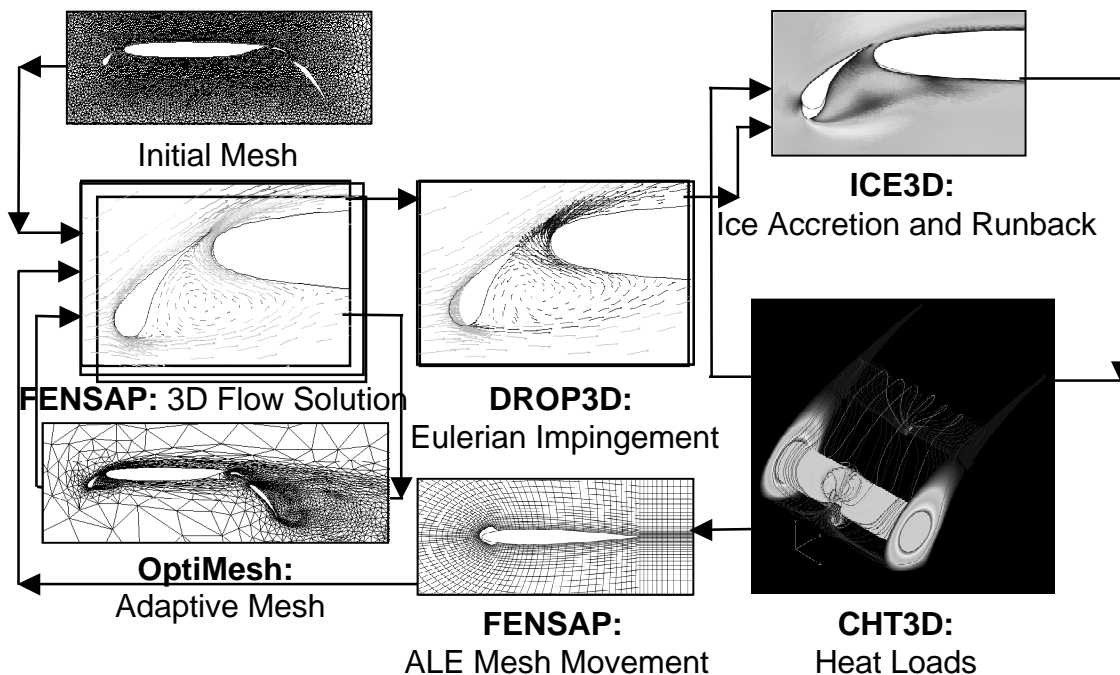
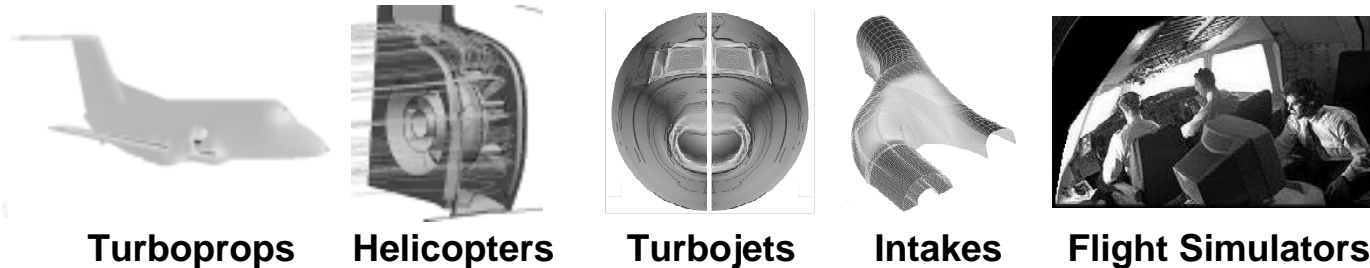
Computational Approach (1)

- The FENSAP-ICE icing simulation system is comprised of 4 modules: clean/degraded flow, droplet impingement, ice growth and conjugate heat transfer
- Non-thermal systems only require flow and droplet impingement for design and analysis
- Hot air and electro-thermal systems design and analysis require water runback, ice growth and conjugate heat transfer



Computational Approach (2)

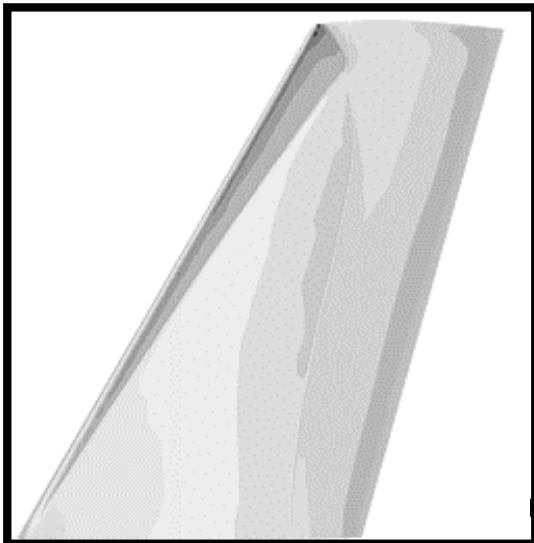
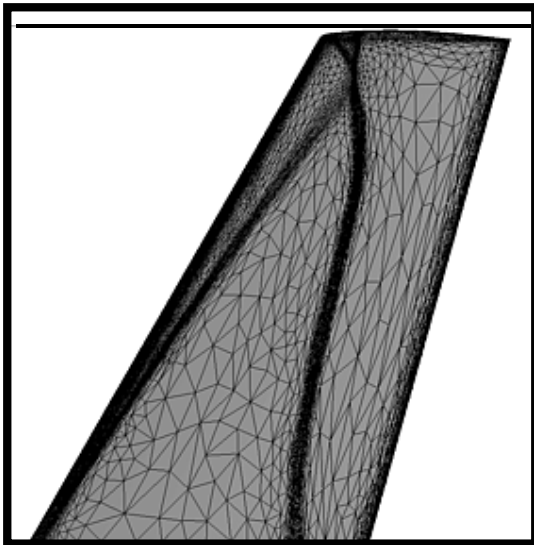
A Second Generation Integrated *System* for
(Aero + In-flight Icing) Simulation and Certification



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Computational Approach (3) - Flow Solver

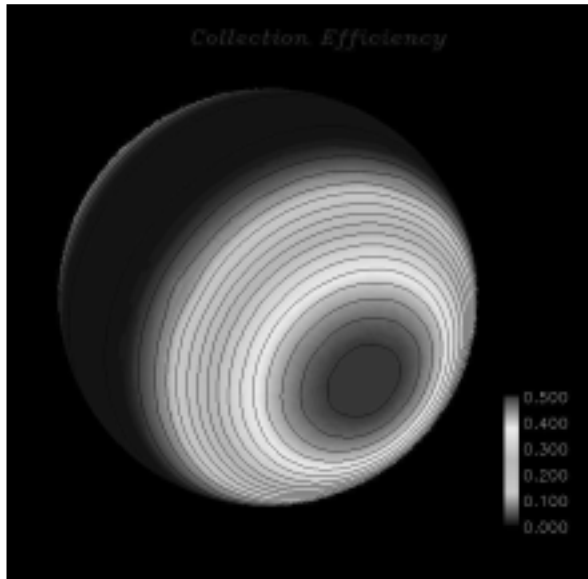


- Any CFD (Euler/N-S) code: shown here is a Fluent solution, after mesh adaptation with OptiMesh
- FENSAP, FENSAP-ICE's native CFD module, is based on FEM
- Includes k-epsilon and k-omega low-Re and high-Re turbulence models
- Includes Spalart-Allmaras turbulence model, with fixed transition and surface roughness
- Includes mesh movement using an ALE method

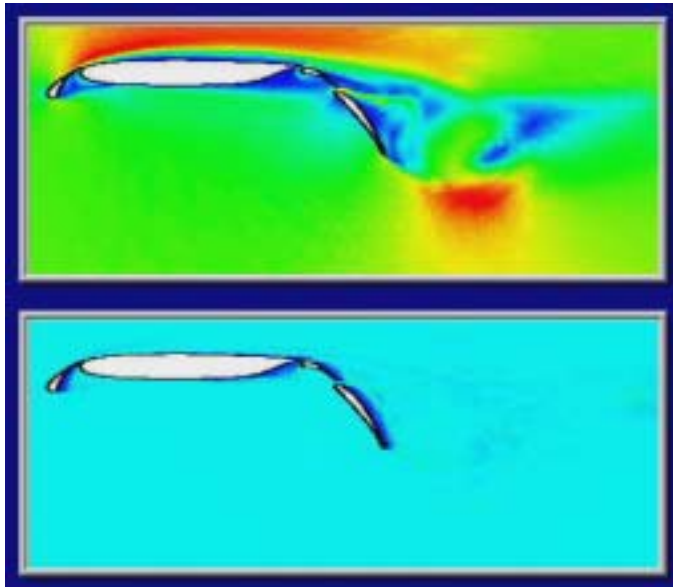
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Computational Approach (4) - Impingement



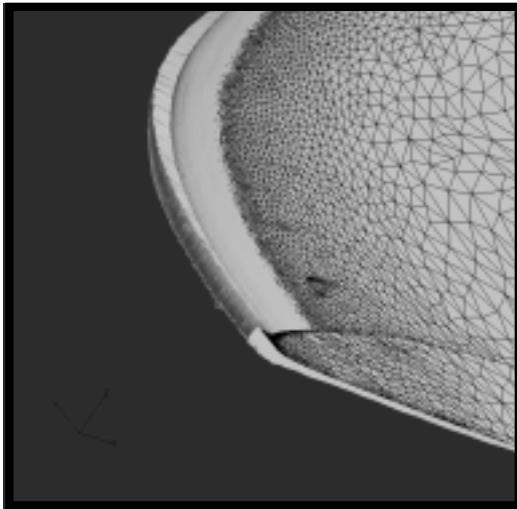
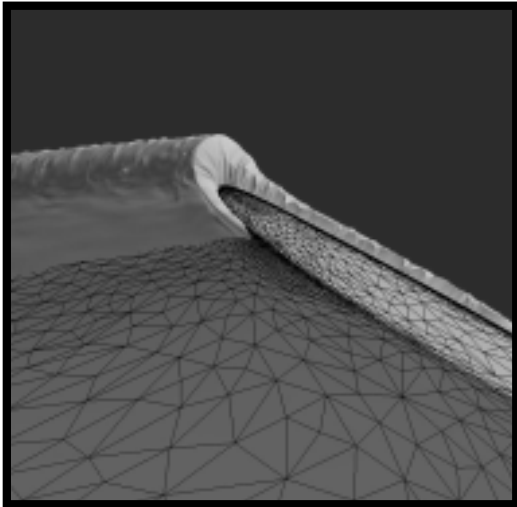
- 3-D Eulerian non-particle-tracking module based on FEM
- Takes into account drag, buoyancy and gravitational forces
- Can simulate supercooled droplets or snow particles
- Produces field values of LWC and droplet velocity, as well as catch efficiencies on all walls



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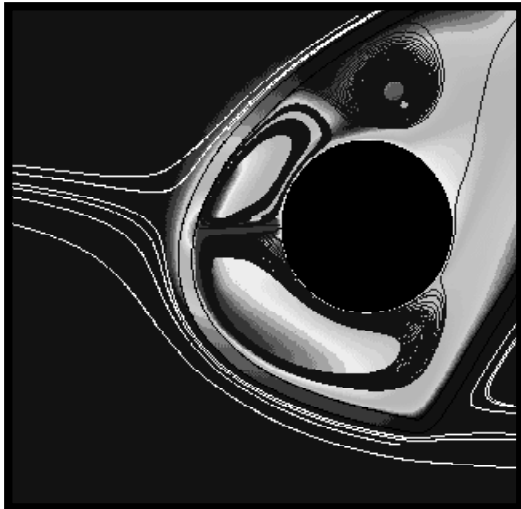
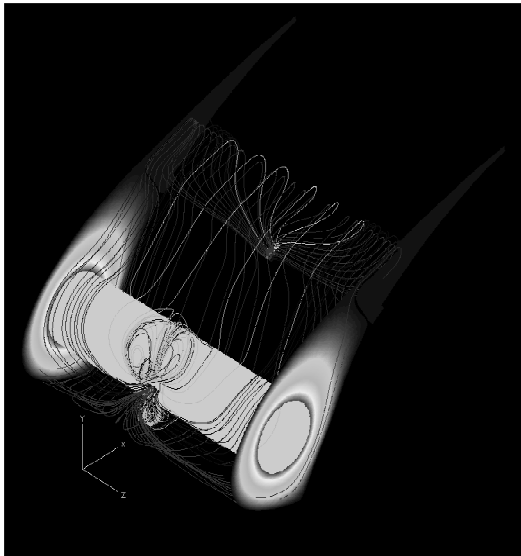


Computational Approach (5) - Ice Growth



- 3-D ice growth module, uses a Finite Volume Method
- Addresses both streamwise and cross-flow directions simultaneously
- Based on the assumption of thin film on the surface
- Does not require empirical relations for convection heat transfer; these are taken from air flow solution

Computational Approach (6) - Heat Transfer

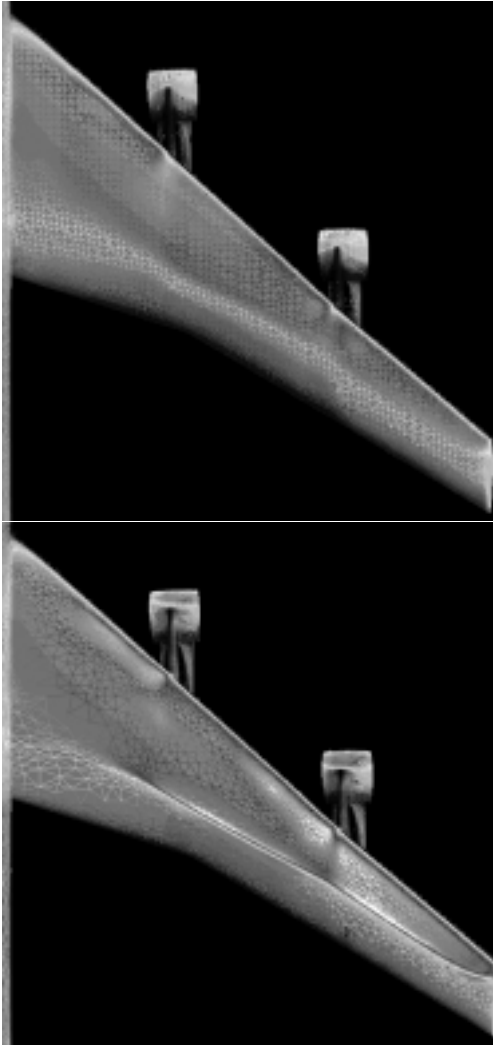


- 3-D conjugate heat transfer interface
- Can be used for any convection-conduction problem, with any number of interfaces
- Includes thin film calculation module for evaporation
- Can accommodate non-matching grids and different types of meshes at all interfaces (any tetrahedral, hexahedral, prismatic, pyramidal or hybrid combinations)

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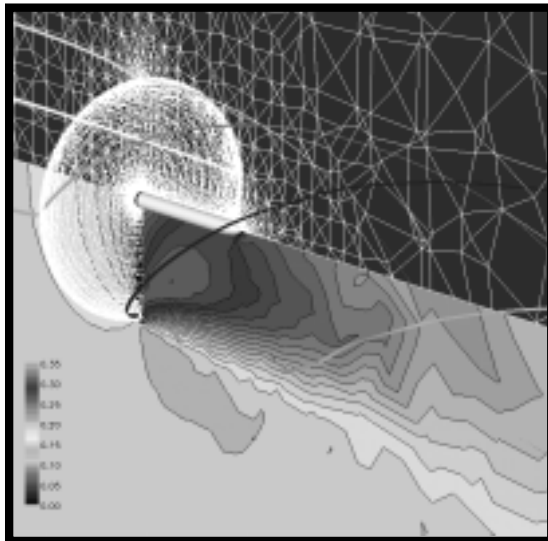
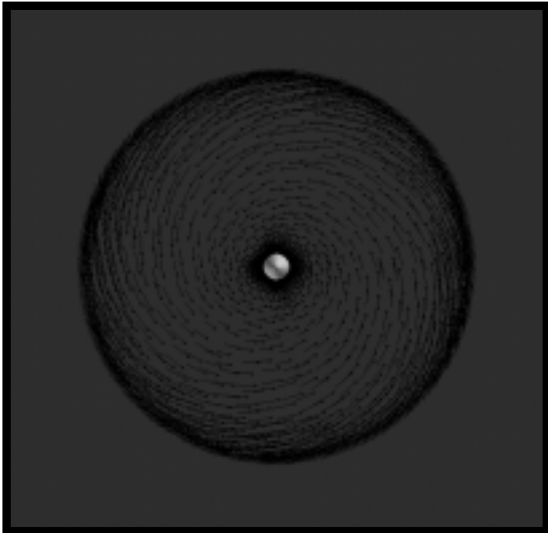


Computational Approach (7) - Adaptation



- Is needed to accommodate the odd shapes of ice (large roughness)
- Edge-based, anisotropic (highly-stretched) mesh adaptation module
- Mesh movement, edge refinement, coarsening, swapping
- Increases accuracy and reduces mesh efforts
- Example shown here is FENSAP Euler solution over a complete 747 (upper portion of wing shown)

Computational Approach (8) - Actuator Disk



- Implementation of a through-flow actuator disk model in finite element
- Infinitely thin disk, without inlet-exit pairs
- Injects adequate amounts of momentum and energy in flow stream
- Satisfies mass conservation and therefore implicitly creates streamtube contraction upstream and downstream of disk
- Disk can be of arbitrary shape and attitude
- Can be used to simulate propellers and rotors, as well as internally for ducted fans

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Numerical Results (1)

- Increasing complexity from:
 - 2-D airfoil
 - 2-D airfoil with flap deployed
 - 3-D wing including sweep and dihedral
 - 3-D wing in tunnel
 - 3-D tiltrotor aircraft without rotors
 - 3-D tiltrotor with rotors
- All test cases run with:
 - Single droplet size
 - Equivalent flight and atmospheric conditions
 - Tiltrotor aircraft components in forward flight configuration
 - Unstructured tetrahedral and prismatic meshing



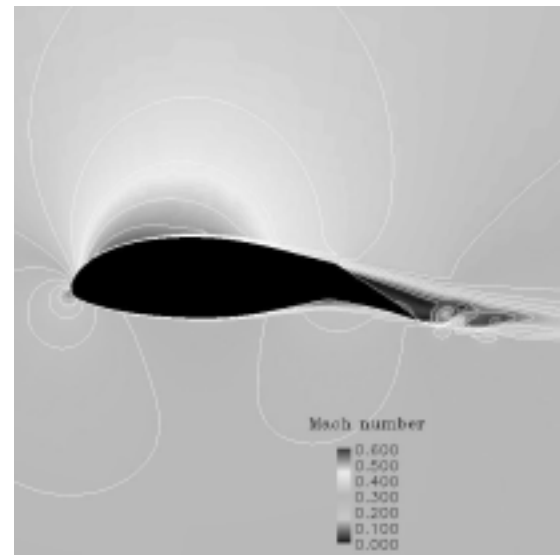
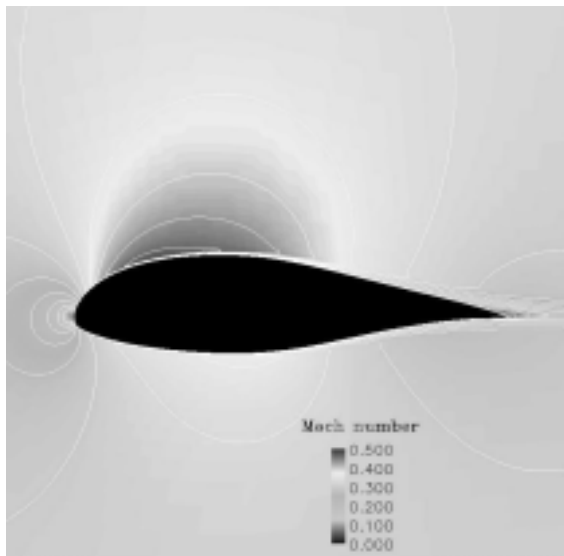
Numerical Results (2)

- Incidence of 3.1° AoA in 2-D and equivalent sectional lift in 3-D
- Altitude of 2694 ft
- Ambient temperature of -4°F
- True airspeed of 194 knots
- LWC of 0.3 g/m^3
- Droplet size of $19.2\text{ }\mu\text{m}$
- Accretion time of 15 minutes



Numerical Results (3)

2-D airfoil without and with 19° flap deflection



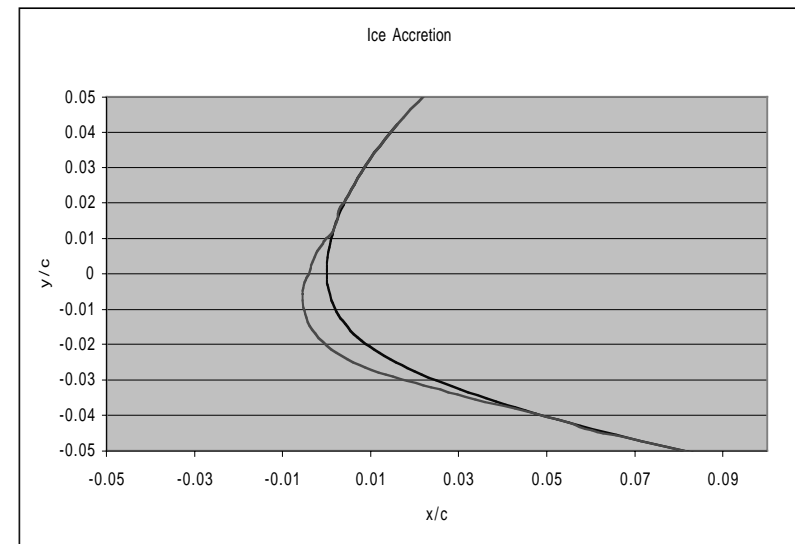
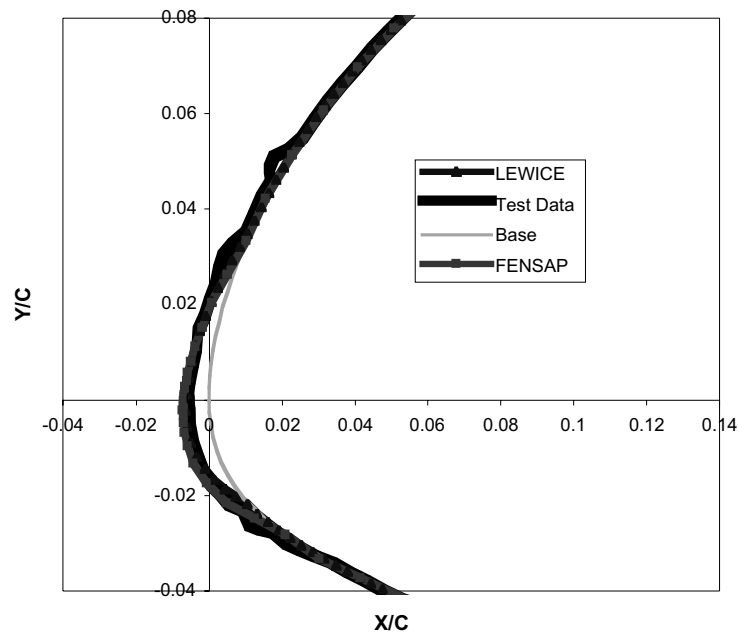
Mach number distribution

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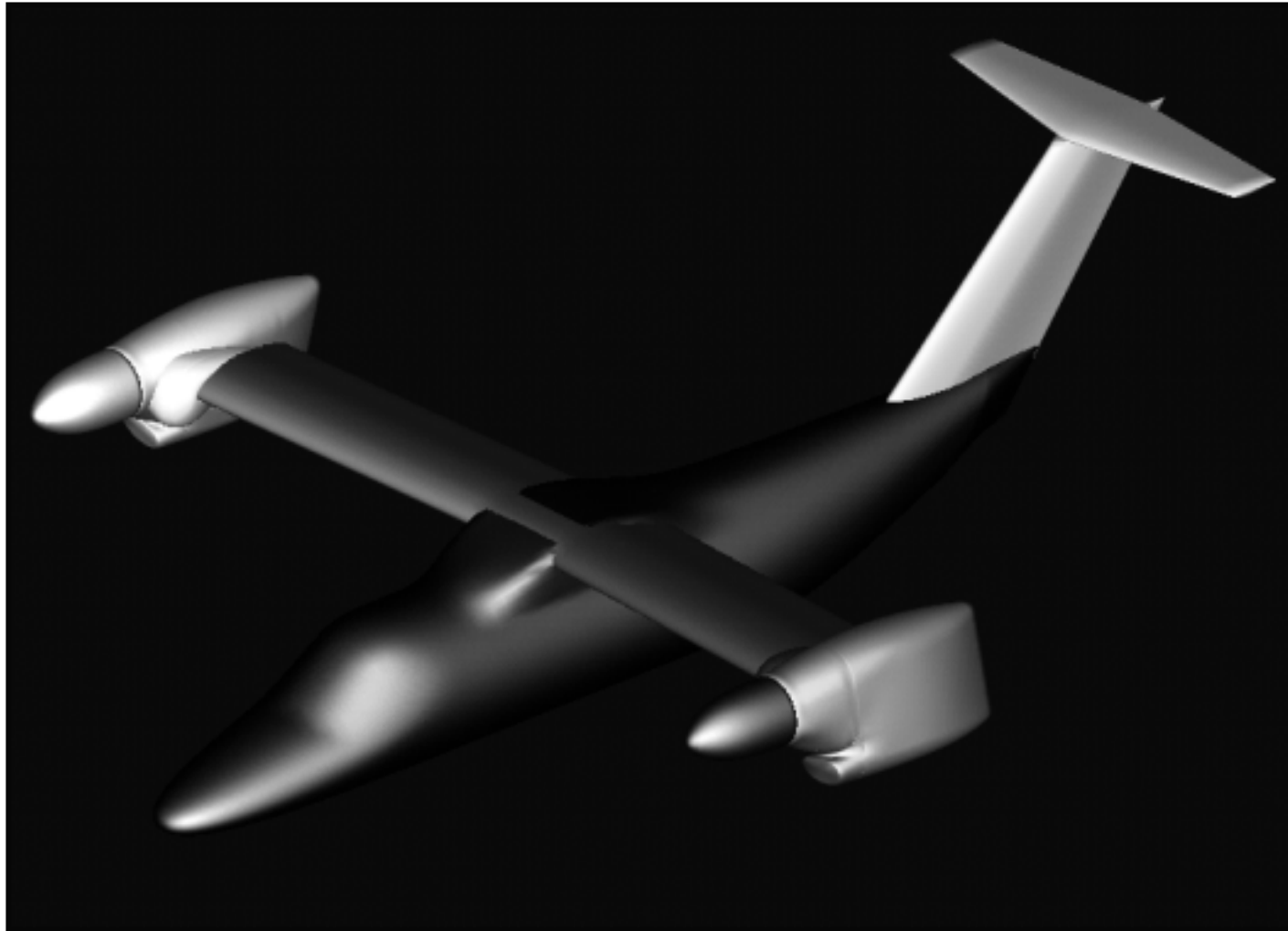
Numerical Results (4)

2-D airfoil without and with 19° flap deflection



Resulting ice shapes

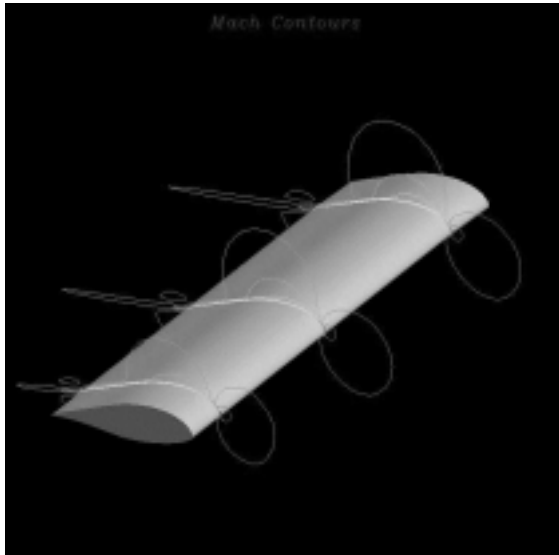
The BA 609



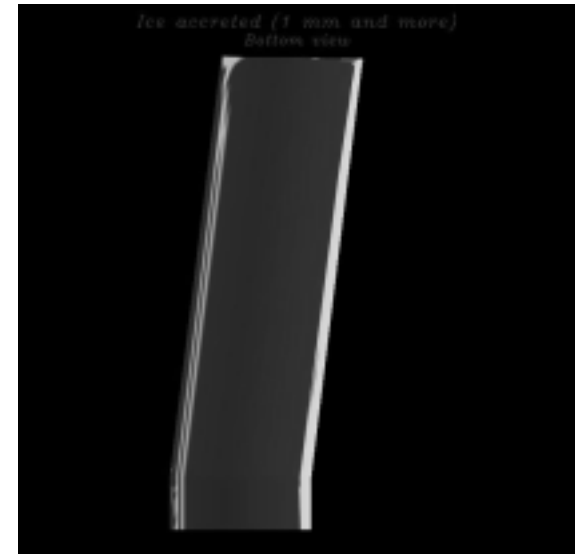
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Numerical Results (5)

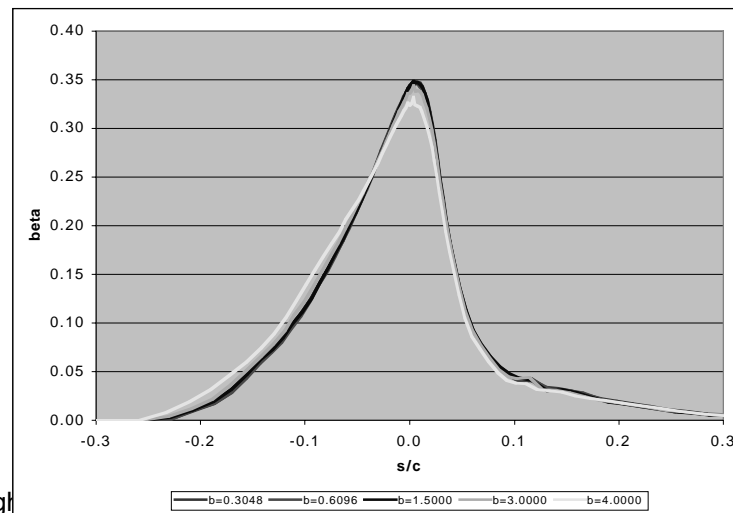


3-D wing



Collection efficiency

Mach number distribution



FAA In-flight

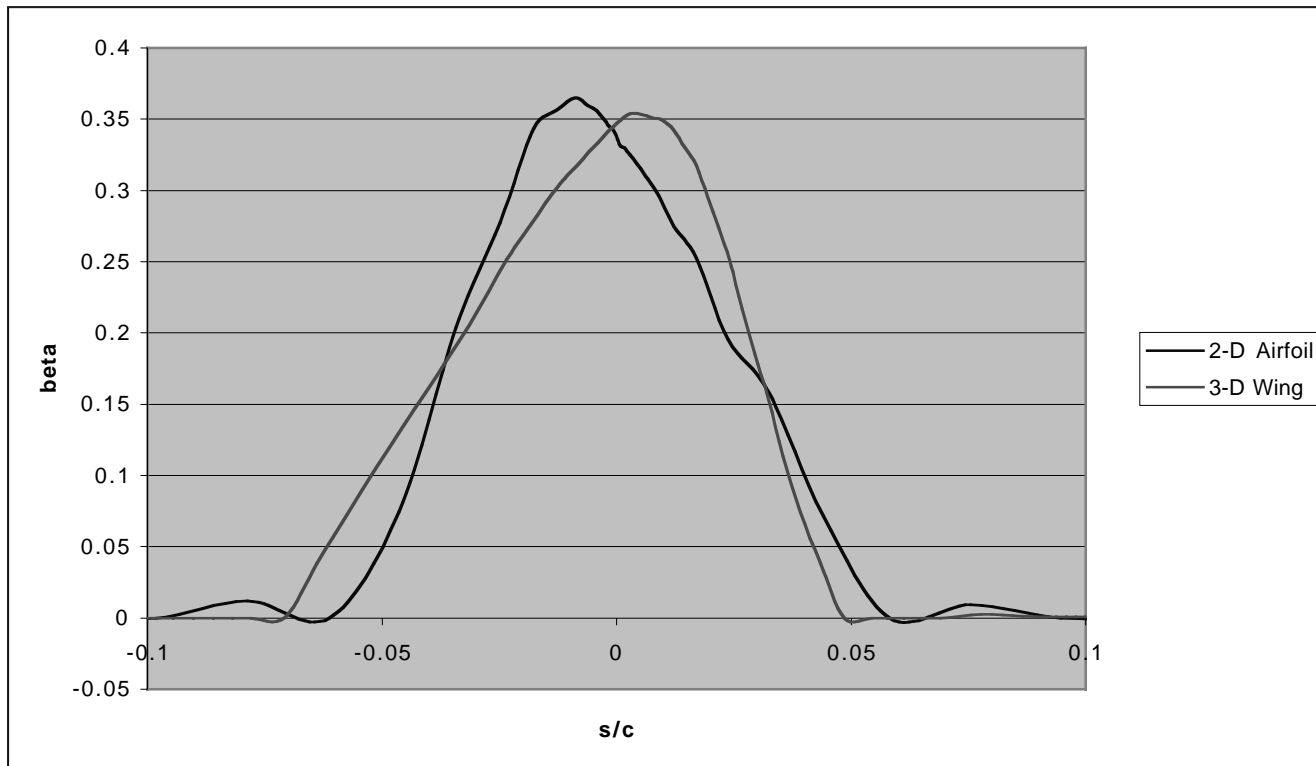
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Resulting ice shape



Numerical Results (6)

- Differences between 2-D airfoil and 3-D wing section are mostly due to tunnel effects



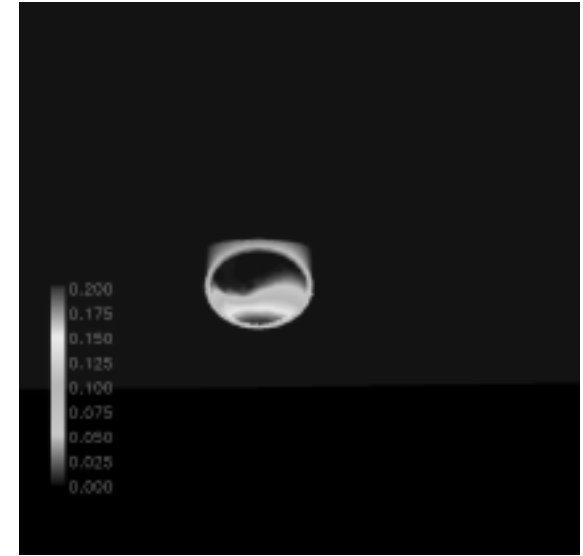
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Numerical Results (7)



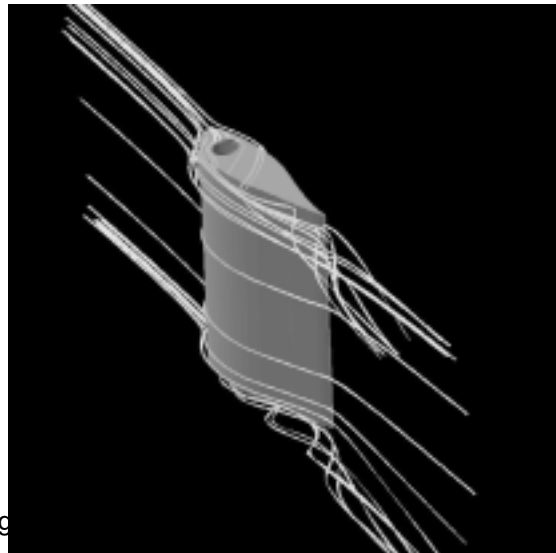
**3-D wing simulation,
including icing tunnel
effects**



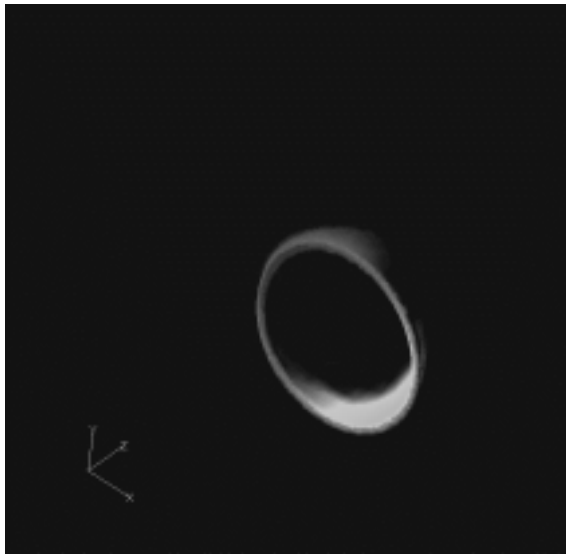
Simulated fuel vent

Collection efficiency

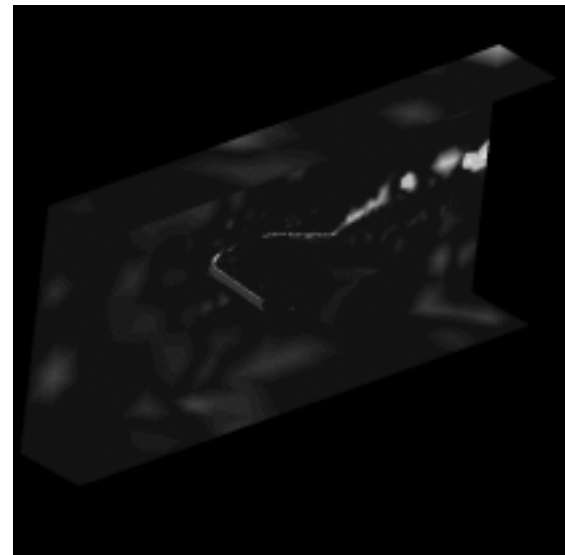
Cylindrical mounts



Numerical Results (8)

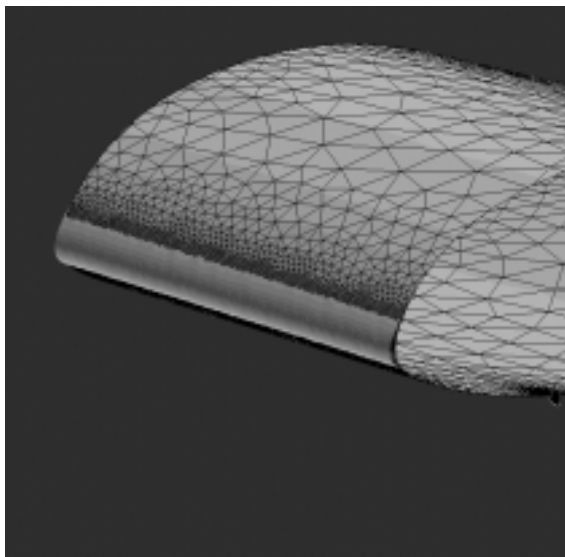


**Collection efficiency on
fuel vent**

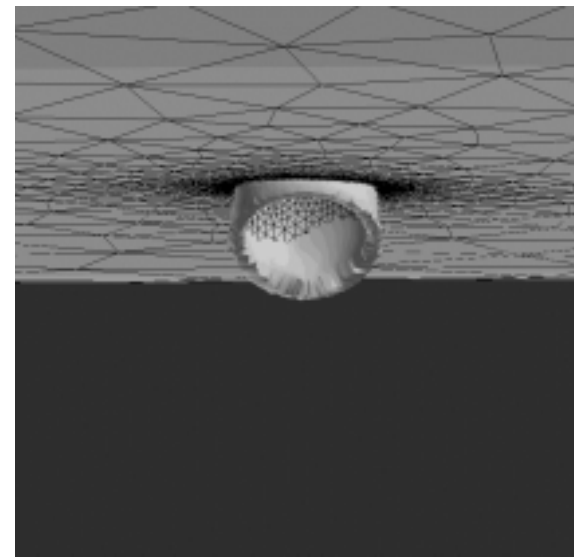


**Collection efficiency
on icing tunnel sidewalls**

Numerical Results (9)



**Ice growth on
wing leading edge**



**Ice growth on
fuel vent**

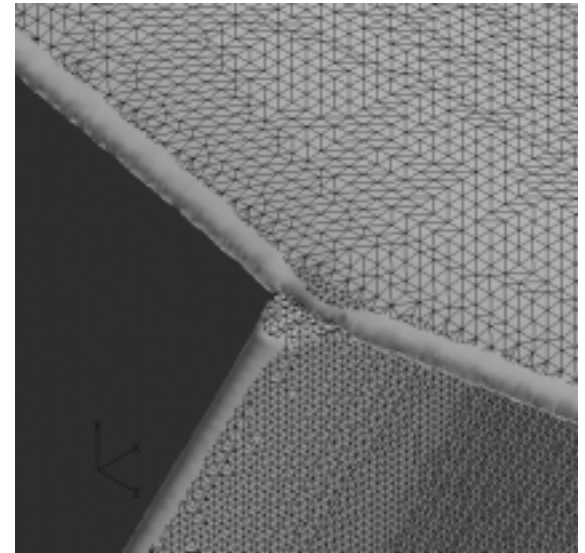
Numerical Results (10)



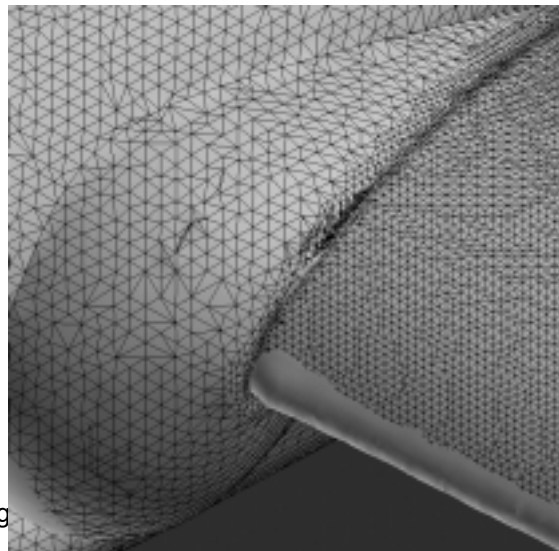
Collection efficiency

**3-D complete
tiltrotor aircraft,
without rotors**

**Ice growth at junction
of outboard wing and
conversion actuator fairing**



**Ice growth at junction of
empennage and stabilizer**



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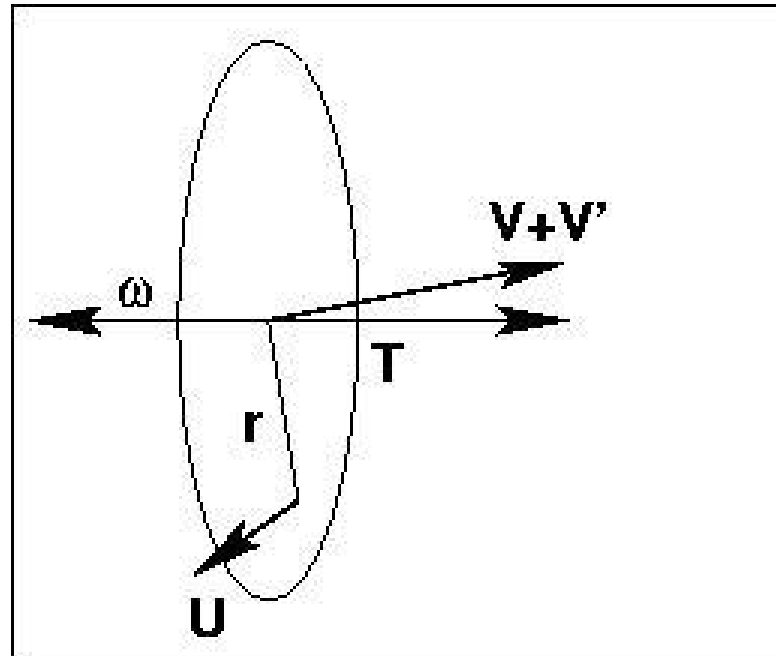


Numerical Results (11)

- Complete tiltrotor aircraft with propellers modeled as actuator disks
- Flow-through actuator disk concept implemented via FEM
- Different from exit/inlet actuator disk concept
- Source terms add momentum, angular momentum, energy and pressure to flow field
- Disks are transparent to droplets, but their effects are felt through the modified flow field



The FEM-based Actuator Disk Model



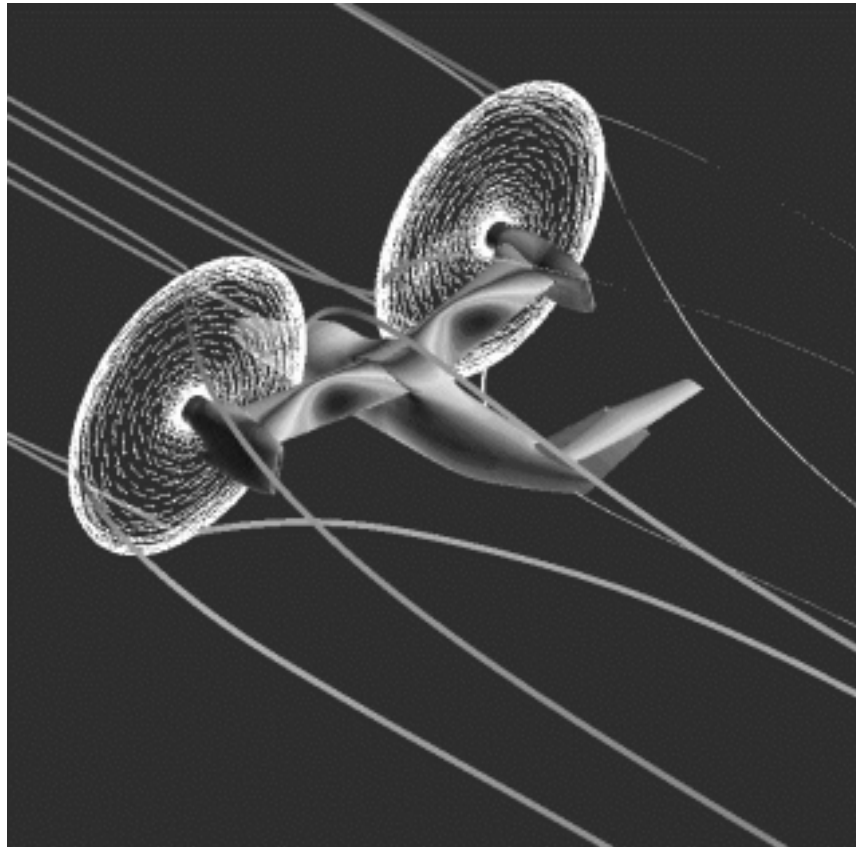
$$\int_V \left\{ W_i \frac{\partial Q}{\partial t} - \left[F(x) \frac{\partial W_i}{\partial x} + F(y) \frac{\partial W_i}{\partial y} + F(z) \frac{\partial W_i}{\partial z} \right] \right\} dV$$

$$+ \int_A W_i \left\{ F(x) n_x + F(y) n_y + F(z) n_z \right\} dA +$$

$$\int_D W_i \left\{ \vec{F} \cdot \vec{n} \right\} dA = 0$$

Numerical Results (12)

3-D complete tiltrotor aircraft, with rotors



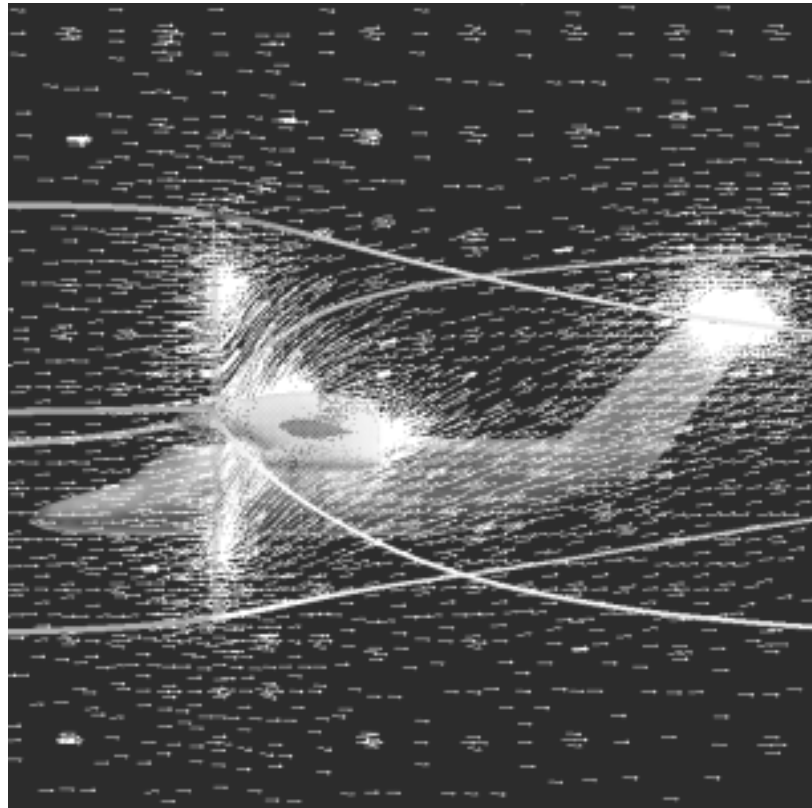
Mach number distribution and streamlines

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Numerical Results (13)

3-D complete tiltrotor aircraft, with rotors



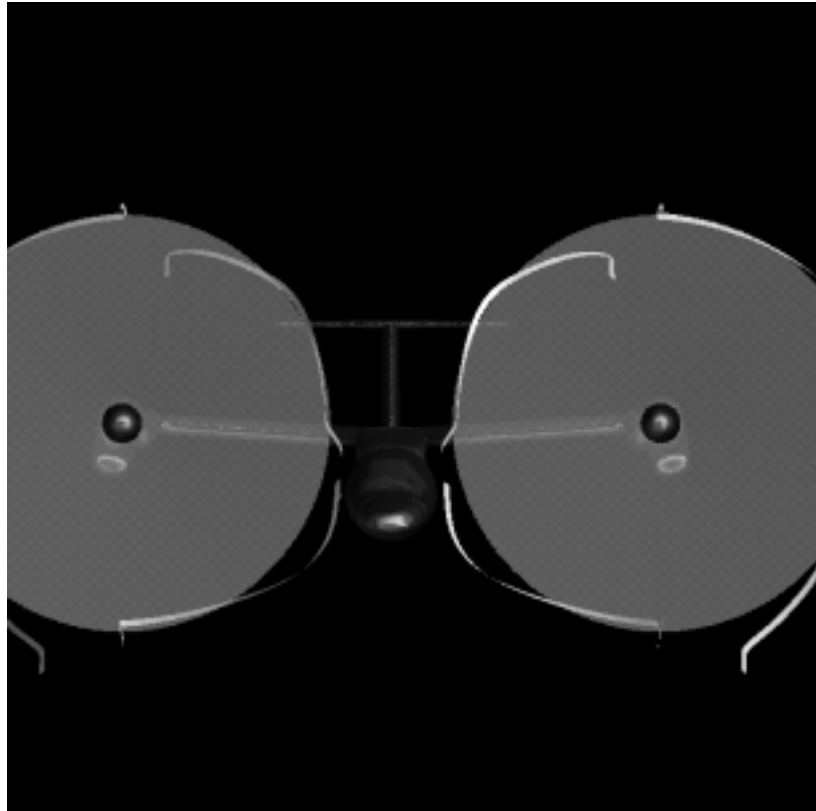
Sectional cut of droplet velocity vectors

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Numerical Results (14)

3-D complete tiltrotor aircraft, with rotors

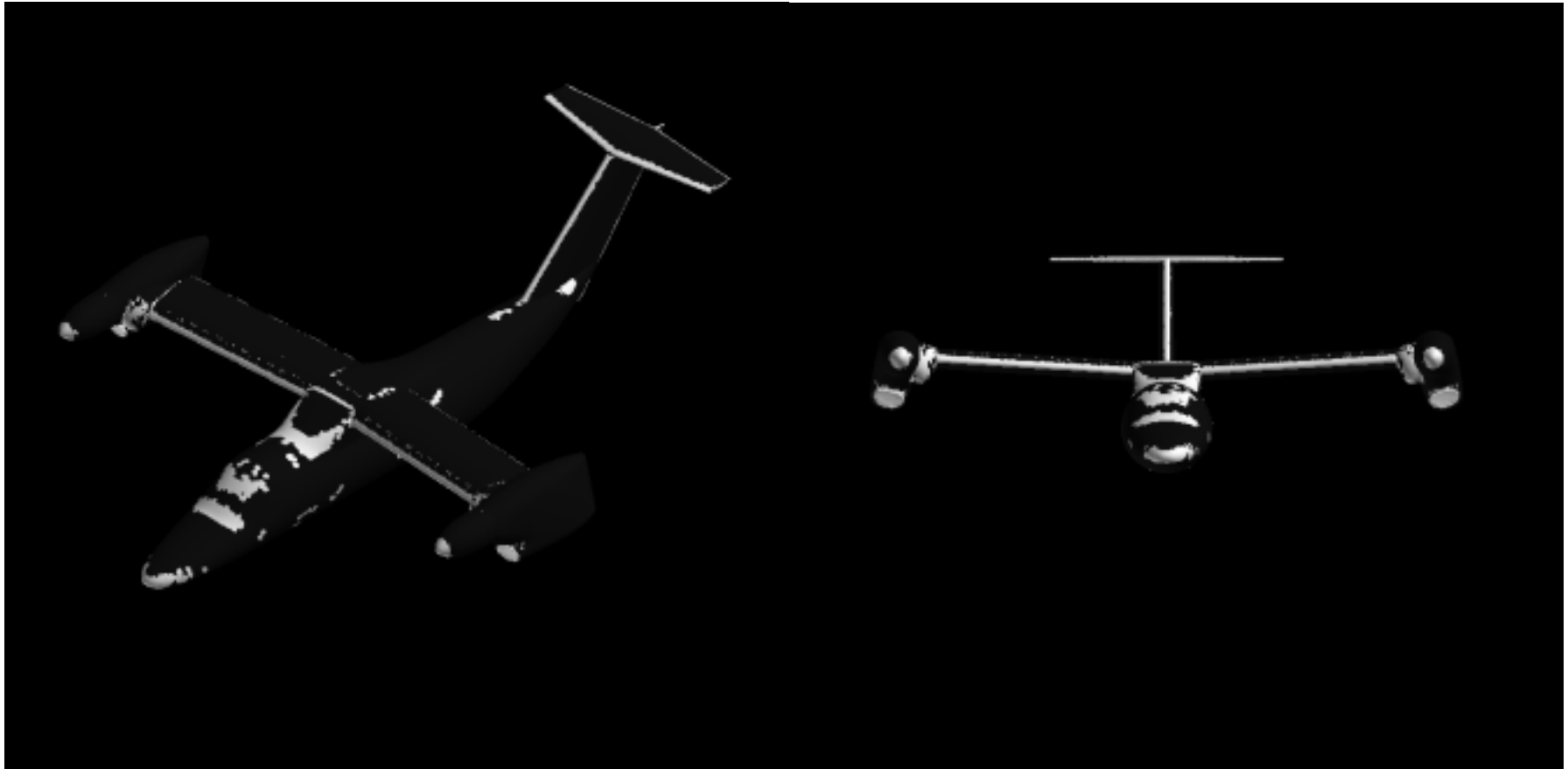


Collection efficiency

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Numerical Results (15)



Ice accretion larger than 1 mm, no rotors, isometric and side views

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Numerical Results (16)



Ice accretion larger than 1 mm, no rotors, top and bottom views

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Numerical Results (17)

- 2-D results do not always provide the real picture
- 3D CFD capability can model complete icing tunnel test section for “correct” experimental comparisons
- Including rotors as actuator disks changes the location of the attachment line and collection efficiency peak



Conclusions (1)

- Method can handle complex geometries of an industrial interest in a cost-effective way
- Incremental cost of icing analysis is small compared to volume mesh generation for complex bodies and flow solution (already done by CFD groups)
- Progress was demonstrated through problems of increasing geometrical complexity



Conclusions (2)

- CFD can complement testing to gain understanding of unavailable conditions
- CFD does not require use of scaling laws and eliminates potential experimental inaccuracies associated with control of water flow rate, relative humidity, temperature, droplet size, tunnel walls, truncated models, etc.
- CFD is another tool in the toolbox of the icing analyst to design improved ice protection schemes



Future Work

- Conduct icing analysis of helicopter in forward flight with main and tail rotors modeled; difficulties are associated with advancing and retreating portions of blade circumference
- Use mesh adaptation strategies to move mesh around iced surfaces; it is expected that it will provide more robustness than ALE, especially for concave surfaces

